REMOVAL OF BENZENE BY THE INDOOR PLANT/ SUBSTRATE MICROCOSM AND IMPLICATIONS FOR AIR QUALITY

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Abstract. The quality of the indoor environment has become a major health consideration, since urban-dwellers spend 80–90% of their time indoors, where air pollution can be several times higher than outdoors. 'Indoor' potted-plants can remove air-borne contaminants such as volatile organic compounds (VOCs), over 300 of which have been identified in indoor air. In this study a comparison was made of rates of removal of benzene, as model VOC, by seven potted-plant species/varieties. In static test-chambers, high air-borne doses of benzene were removed within 24 h, once the response had been stimulated ('induced') by an initial dose. Removal rates per pot ranged from 12–27 ppm d^{-1} (40 to 88 mg m^{-3} d^{-1}) (2.5 to 5 times the Australian maximum allowable occupational level). Rates were maintained in light or dark, and rose about linearly with increased dose. Rate comparisons were also made on other plant parameters. Micro-organisms of the potting mix rhizosphere were shown to be the main agents of removal. These studies are the first demonstration of soil microbial VOC degradation from the gaseous phase. With some species the plant also made a measurable contribution to removal rates. The results are consistent with known, mutually supportive plant/soil-micro-organism interactions, and developments in microbially-based 'biofilter reactors' for cleaning VOC-contaminated air. The findings demonstrate the capacity of the potted-plant microcosm to contribute to cleaner indoor air, and lay the foundation for the development of the plant/substrate system as a complementary biofiltration system.

Keywords: benzene, biofiltration, indoor air quality, indoor plants, micro-organisms, VOC

1. Introduction

The quality of the indoor environment has become a major health consideration in the developed world, since urban-dwellers generally spend 80–90% of their time indoors (Abbritti and Muzi, 1995; Krzyanowski, 1999; Carpenter, 1998; American Lung Association, 2001). The quality of indoor air is of particular concern, with over 300 volatile organic compounds (VOCs) having been detected as contaminants thereof. Although each compound is likely to be present in very low concentrations, the mixture can produce additive and possibly synergistic effects (National Occupational Health and Safety Commission (Australia) (NOHSC), 1991; American Conference of Government and Industrial Hygienists, ACGIH, 1994–1995; Weschler and Shields, 1997; World Health Organization, 2000). Indoor air can

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often contain 5 to 7 times the contaminant concentrations of outdoor city air (Brown *et al.*, 1994; Brown, 1997). The harmful effects of these mixtures have been recognized as components of 'sick building syndrome' or 'building-related'(Brasche *et al.*, 1999; Carrer *et al.*, 1999), with symptoms of headache, dizziness, nausea, sore eyes and throat, or loss of concentration.

There is a growing body of evidence that 'indoor' potted-plants can make a significant contribution to the removal of air-borne contaminants, including dust, inorganic gases, and VOCs (Wolverton *et al*., 1989; Wolverton Environmental Services Inc., 1991; Wolverton and Wolverton, 1993; Giese *et al.*, 1994; Lohr and Pearson-Mims, 1996; Coward *et al*., 1996; Wood *et al*., 2000, 2001, 2002; Tarran *et al*., 2002). Wolverton and Wolverton (1993) suggested that growth media micoorganisms might also play an important role in VOC removal.

The aim of the current investigation was to compare VOC removal rates among seven internationally used interior potted-plant species, using benzene as the model contaminant. Quantitative, comparative information on VOC removal is required to establish both the current usefulness of the system, and the provision of information for the development of a flexible plant-based biofiltration system which could complement engineering measures to improve indoor air quality. Removal rates were compared in static test-chambers under several conditions: on initial exposure to the VOC; after induction of a more rapid response; under light and dark conditions; and with both repeated 'standard' (equal to initial) and higher doses.

It is well known that 'outdoors' plants can absorb toxic compounds from the air, including VOCs such as benzene and toluene and semi-volatile organics (SVOCs) such as anthracene, and sequester or detoxify them, or metabolise (biodegrade) them to yield carbon dioxide and water (Ugrekhelidze *et al*., 1997; Cape *et al*., 2000; Collins *et al*., 2000; Howsam *et al*., 2001; Komp and McLachlan, 2001; Peck and Hornbuckle, 2002). For this reason, plants have been extensively used as biomonitors of outdoor air pollution (Omasa *et al*., 2002). A number of soil micro-organisms can degrade liquid-phase petroleum-based compounds to carbon dioxide, and hence plants and their soil microbial populations have been used to clean up soils contaminated with oil spills (Radwan *et al.*, 1998; Newman *et al.*, 1998; Nemergut *et al*., 2000; Pucci *et al*., 2000).

Our own previous studies, using three commonly used interior foliage plant species (Wood *et al*., 2000, 2001, 2002) showed that potted specimens in static test chambers, after an introductory period of exposure, could within 24 h remove several times the maximum allowable Australian occupational exposure levels of benzene and *n*-hexane, two common contaminants of the indoor environment. The results also showed that, under these test conditions, in these species, it was the rhizosphere micro-organisms in the potting mix that were the significant direct agents of VOC removal. Unused potting mix alone was also found to display some VOC removal activity, although at significantly lower rates than with the plant present, and prone to exhaustion within 2 wks. In contrast, with the plant growing in the

potting mix, removal rates could be sustained for experimental periods of up to 40 days. Soil micro-organisms are components of potting mix, although different plant species develop distinctive assemblages of root-zone micro-organisms (Anderson *et al*., 1993; Burken and Schnoor, 1996; Schwab *et al*., 1998). It is also known plants can secrete up to 40% of their net photosynthetic product from their roots to select and sustain their species-specific micro-organism community, and that the root exudates cause and maintain increases in total numbers of micro-organisms in the rhizosphere by orders of magnitude over those in the bulk soil (Brigham *et al*., 1994; Darlington *et al*., 2000).

In the experiments reported here, the plant species included the three, we had previously studied, *Howea forsteriana* (Kentia Palm), a cultivar of *Spathiphyllum floribundum,* var. Petite (Peace Lily) (*S*. 'Petite'), and *Dracaena deremensis* var. Janet Craig (*D*. 'Janet Craig'), along with four other internationally used species/varieties which had not previously been investigated. These included a second variety of *S. floribundum*, var. Sensation (*S*. 'Sensation'), a second species of *Dracaena, D. marginata*; plus *Epipremnum aureum (*Devil's Ivy); and *Schefflera actinophylla* var. Amate (Queensland Umbrella Tree) (*S*. 'Amate'). For each plant type, the relative roles of plant and potting mix micro-organisms in the VOC removal were investigated.

2. Materials and Methods

2.1. Plant materials

Well established 12-month old specimens of each plant species were used (4 replicates per species), 0.3–0.4 m in height, in pots 150 mm diameter, in a standard potting mix consisting of composted hardwood sawdust, composted bark fines, and coarse river sand (2:2:1) (bulk density $\sim$0.6 g mL^{-1}; air-filled porosity $\sim$30%), with Macracote "green-plus" 9-month fertilizer (12:4.6:10 N:P:K, with trace elements; Langley Chemicals, Welshpool, WA). In order to carry out various inter-species comparisons of VOC removal capacity, several plant morphological characteristics were measured, including total leaf area, using a leaf area meter (Licor LI-3000-A, Nebraska); and dry weight (dwt) of shoots, roots, and potting mix, using a drying oven at 70 °C for 24 h.

2.2. Apparatus

Four replicate perspex bench-top test chambers were used, 0.6 $\times$ 0.6 $\times$ 0.6 m (internal volume 0.216 m^3), with removable lids on stainless steel frames, sealed with adhesive foam-rubber tape and metal clips. Each chamber had rubber septa for VOC injections and air sampling; a 0.5 m coil of copper tubing (i.d. 4 mm) circulating water from a thermostat bath at 23° $\pm$ 0.1°C; a suspended mini-max

thermometer; a 2.4 W fan to accelerate atmospheric equilibration; an overhead light box (with air gap of 50 mm) with five 18 W fluorescent tubes designed for optimum plant growth (Wotan L 18/11 Maxilux Daylight, Ozram, Germany) ($\sim$120 μmol quanta m^{-2} s^{-1}). Chambers were darkened when necessary by covering with sheets of black plastic.

2.3. PROCEDURE

The potted-plants were watered to saturation and allowed to drain for 1 h before being placed one in each chamber, with lids sealed and lights on ($\sim$120 μM m^{-2}). An initial dose of 25 ppm (80 mg m^{-3}) benzene was injected onto suspended paper tissue in each chamber, this being five times the allowable occupational maximum in Australia (National Occupational Health and Safety Commission (Australia), 1991). For each subsequent sampling, 1.0 mL of chamber air was withdrawn in a gas-tight syringe. Chambers were sampled in duplicate, and benzene concentrations analyzed over time, using a gas chromatograph (GC; Shimadzu GC-8A). Calibrations were performed using standard gas samples. Applied benzene concentrations were found to equilibrate in the chambers in about 1.5 h. The lower limit of detection of the GC was 0.09 ppm (0.3 mg m^{-3}) benzene. Samplings were carried out at hourly, several hourly or daily intervals as required. Additional 'top-up' injections to the original concentration were performed as needed for each stage of the experiment. In longer trials, plants were watered twice weekly via a tube inserted through the septum into the pot. Plants were later removed and the pots with potting mix replaced into the chambers, which were sealed and given a new dose of the VOC. Prior to plant removal, the pots were well watered, and plants gently extracted with the aid of a spatula, removing as little substrate as possible; roots were then washed from a wash bottle to return adhering particles to the pot. Leak tests were carried out before and/or after each experiment. Losses were found to be 2.7–3.8% per day for 25 ppm benzene, and results were corrected accordingly. No differences in leakage rates were found between light and dark conditions, or with empty pots and tubing alone. The benzene was Analar grade (BDH Chemicals Australia Pty Ltd, Port Fairy, Vic.). Experiments were commenced under continuous light ($\sim$120 μmol quanta m^{-2} sec^{-1}) such as is often found in public indoor environments (eg., hotels, shopping malls, many office blocks, hospitals, airports). A dark regime was later imposed. The full experimental sequence for each plant species was as follows (though in some cases, for practical reasons, some stages were omitted):

a) *With initial dose of VOC* (25 ppm benzene) in light conditions, initial removal rates were measured at hourly to two-hourly intervals over 8 h, then overnight, for potted-plant acclimation to exposure to the VOC.
b) *Continued sampling after initial dose*, daily over the next two or more days (as necessary) was conducted, to measure the induction of a stimulated response,

i.e. increased removal rates produced by this single dose (this usually occurred within 2 days).

c) *Repeated 'top-up' doses to original concentration* were then applied, and removal rates measured over successive 24 h intervals, to test for either maintenance of rate or induction of further rises in activity.
d) *Dark regime* was then imposed (which closes stomates and hence diffusion to and from leaf mesophyll, and prevents photosynthesis, but does not directly affect microbial metabolism); removal rates were measured and additional top-up injections applied, again at 24 h intervals.
e) *Higher VOC dose* was then applied, still in the dark, to investigate dose-response reactions. The dose was doubled, to 50 ppm (160 mg m^{-3}) benzene.
f) *Plant removed*, and the activity of the potting mix alone was tested by being placed back in the chamber, still in the dark, with a new, 'standard' dose of the VOC (i.e. 25 ppm benzene).

2.4. Microbiological procedures

To test specifically the VOC removal rates of the potting mix of each plant species, 50 g samples were taken from each of three pots after completion of the test-chamber experiments, and aseptically transferred to gas-tight testing jars fitted with silicon rubber septa. In addition, to examine the activity of any bacterial colonies derived from the potting mix, for each species, from the same three pots, 5 g potting mix samples were taken and aseptically used to make 10^{-2} suspensions in 0.1% sodium pyrophosphate solution. A 0.1 mL aliquot of each suspension was then used to inoculate 50 mL of 10th-strength tryptic soy broth (Oxoid), which was poured on to 8 g of sterile grade-3 vermiculite as a high-surface-area growth-support medium (Wood *et al*., 2002). Each broth/suspension culture slurry was aseptically sealed in a gas-tight jar. Benzene vapour to give a concentration of 25 ppm benzene, was injected into the jars containing either potting mix or culture suspensions, and they were monitored after 24 h, when a top-up dose was added as required. Benzene concentrations were again monitored at 48 and 72 h, before once again being topped-up to 25 ppm, to be measured finally at 96 h. Thus, the benzene level was topped-up three times, to establish that biodegradation of the VOC could occur *in vitro*.

2.5. Statistical analysis

Means ($n = 4$) and standard errors (SE) were calculated. Single factor analyses of variance (ANOVA; Microsoft Excel 5.0) and post hoc pair-wise comparisons using either Bonferroni T-tests (VOC removal data) or Tukey's Honestly Significant Difference test (microbiological data) were used to analyse the results. For all experiments, differences were regarded as significant where $p \leq 0.05$.

3. Results

3.1. Plant shapes and sizes

Plant and potting mix parameters are summarised in Table I. Plant proportions varied considerably among species, for example, *S*. 'Petite' and *H. forsteriana* had three to four times as much leaf area as the last four listed, that is, *E. aureum, S*. "Sensation', *S*. 'Amate' and *D*.'Janet Craig'. Shoot dry weights varied to a lesser extent than leaf area (within a factor of 1.5), values tending to increase with decreasing leaf area, indicating more fibrous tissue. Root weights varied much more widely than shoot parameters (ranging with a factor of 10). There were also inter-species differences in the ratios of shoots/roots, which reflect different strategies of resource allocation by the plants. All such differences are visible signs of different plant/soil relationships among species, which in turn will affect plant/root zone (rhizosphere) micro-organism relationships. Conceivably, such differences in attributes could result in differences in VOC removal propensities. Since in the international horticultural industry the unit of plant usage is generally per 'pot of specified size' (which gives a reasonable idea of the size and shape of the specimen), the results here are first considered on a per-pot basis (i.e.,

TABLE I

Physical characteristics of plants and potting mixes for the plant species tested, in descending order of leaf area

	Plant and potting mix characteristics				
Plant species	Leaf area (m^2)	Shoot dwt (g)	Root dwt (g)	Potting mix dwt(g)	Shoot/ Root
Spathiphyllum 'Petite'	0.90 ± ~0	11.3 ± 0.5	4.3 ± 0.8	352 ± 14	2.6
Howea forsteriana	0.80 ± 0.01	11.1 ± 1.1	3.3 ± 0.2	810 ± 26	3.3
Dracaena marginata	0.65 ± 0.01	16.1 ± 2.3	12.2 ± 4.3	805 ± 26	1.3
Epipremnum aureum	0.26 ± ~0	11.1 ± 0.1	26.2 ± 2.5	714 ± 15	0.42
Spathiphyllum 'Sensation'	0.26 ± 0.02	5.7 ± 0.9	9.3 ± 0.5	427 ± 22	1.7
Schefflera 'Amate'	0.15 ± ~0	15.5 ± 103	1.7 ± 0.1	385 ± 12	9.1
Dracaena 'Janet Craig'	0.15 ± 0.01	17.6 ± 1.0	4.5 ± 0.7	452 ± 18	3.9

Values are means ± S.D. ($n = 4$).

per-chamber). They are then also considered on the basis of the alternative plant and potting mix parameters, which may be of future importance in research and development of the potted-plant system for the further development of air-cleansing properties.

3.2. RATES OF BENZENE REMOVAL PER POTTED-PLANT

Patterns of benzene removal per potted-plant (i.e., per chamber) for each species are shown in Figures 1 and 2, and a comparative summary of 24-h-averaged rates at the later (post-induction) stages of the experimental sequence is presented in Table II. There were strong similarities of response across all species/varieties. In each case, during acclimation following the initial dose of VOC (stage *a* of experimental sequence) removal rates were initially slow (<1.5 ppm d^{-1}) but then increased markedly (6–9 ppm d^{-1}) (stage *b*), indicating the induction of a more rapid removal ability, usually within 2–4 days of exposure. A higher rate of activity

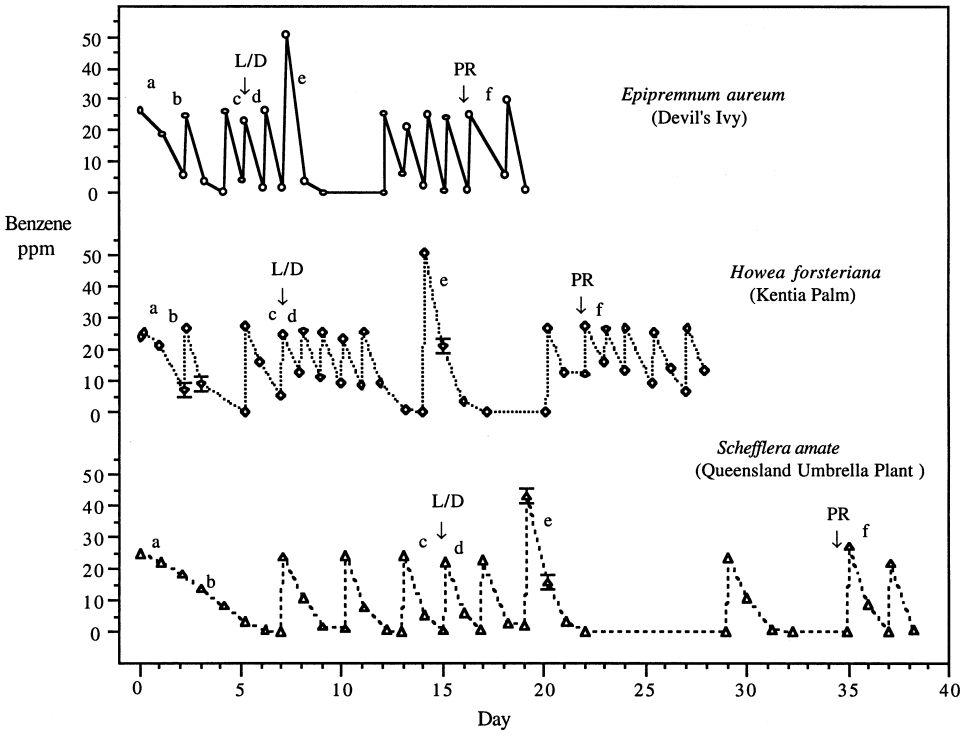

Figure 1. Concentrations of benzene in chambers with potted *Epipremnum aureum*, *Howea forsteriana* and *Schefflera* 'Amate'. Step increments indicate injections of benzene (to 25 or 50 ppm). L/D = from light to dark conditions; PR = plant removed, potting mix returned to chamber. Values are means ± S.D. ($n = 4$).

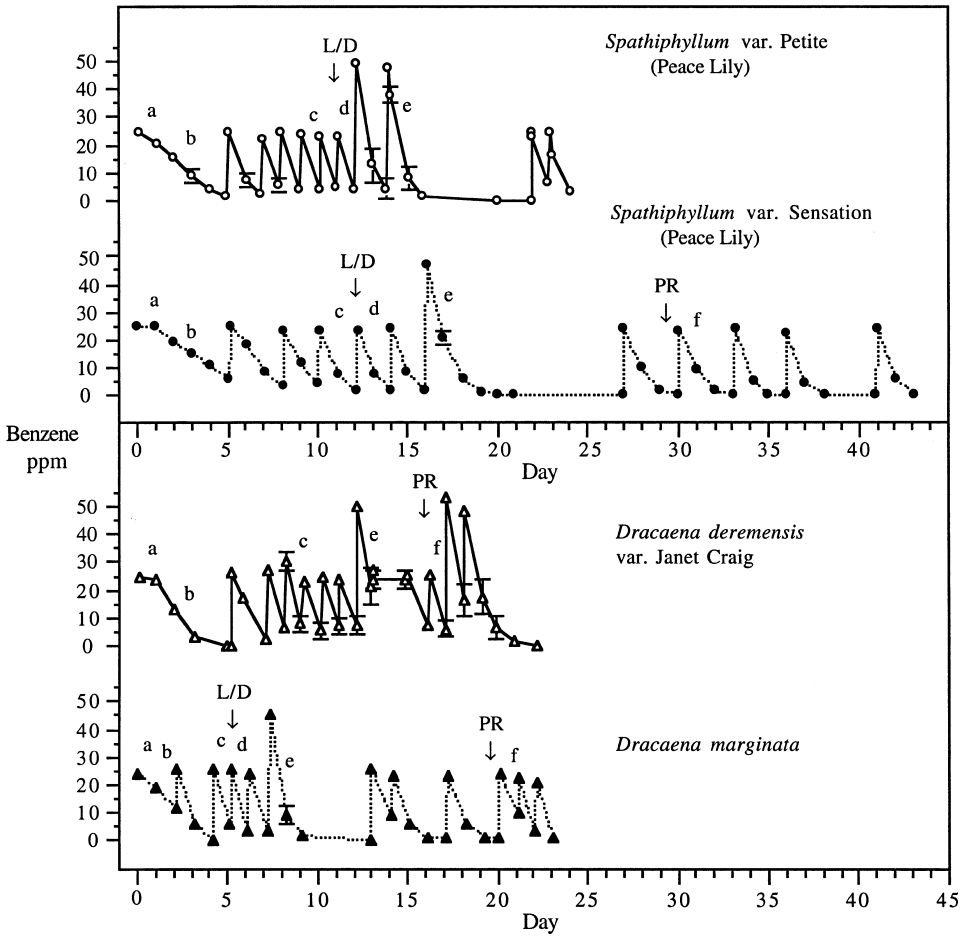

Figure 2. Concentrations of benzene in chambers with potted *Spathiphyllum* 'Petite', *Spathiphyllum* 'Sensation', *Dracaena*. 'Janet Craig', and *Dracaena marginata*. Step increments indicate injections of benzene (25 or 50 ppm). L/D = from light to dark conditions; PR = plant removed, potting mix returned to chamber. Values are means ± S.D. ($n = 4$).

was in each case stimulated by the initial exposure to the chemical. With further topping-up doses (stage *c*) the induced higher activity was either maintained or further increased to a new steady level (Table II).

When dark conditions were imposed (stage *d*) in all species rates either remained unaltered or, in the case of *E. aureum*, actually rose slightly (Table II). The results suggest a primary VOC removal role for the potting mix micro-organisms, since, in the dark, the leaf stomates are closed and hence stomatal leaf diffusion processes are halted, as is photosynthetic metabolism, which might otherwise be linked with degradation pathways of the VOC. Furthermore, it was found that when, still in the dark, a higher benzene dose was then applied (stage *e*), removal rates

TABLE II

Rates of benzene removal (24 h-averaged) with 25 ppm doses (or 50 ppm), in the stages of the experimental sequence after induction of higher rates of response

	24 h-averaged rate of VOC removal (ppm d^{-1} per plant) stage of experimental sequence			
Plant species	*c* Induced by repeated doses (in light)	*d* Moved to dark	*e* Doubled dose (in dark)	*f* After plant removal (in dark)
Dracaena 'Janet Craig'	27.5 ± 6.9 (*7*)	–	38.8 ± 8.4	15.2 ± 1.7
		(*c*)[a]	(*c*, *d*)	(*c*, *d*, *e*)
Epipremnum aureum	23.5 ± 0.03	28.0 ± 0.5 (*4,5,6,7*)[b]	49.3 ± 0.5 (*5*)	10.6 ± 0.4
			(*c*, *d*)	(*c*, *d*, *e*)
Dracaena marginata	24.7 ± 1.1	24.0 ± 1.2 (*2,4,5*)	39.7 ± 2.2	13.4 ± 1.3
			(*c*, *d*)	(*e*)
Schefflera 'Amate'	19.0 ± 1.2	17.8 ± 0.6 *(2,3,7)*	28.2 ± 1.6	14.0 ± 1.1
			(*c*, *d*)	
Spathiphyllum 'Petite'	18.8 ± 1.8	19.0 ± 1.4 (*2,3,7*)	40.9 ± 6.8	–
			(*c*, *d*)	(*e*)
Spathiphyllum 'Sensation'	15.5 ± 0.5	16.1 ± 0.7 (*2,3*)	27.5 ± 2.5 (*1*)	14.2 ± 0.7
			(*c*, *d*)	(*e*)
Howea forsteriana	12.6 ± 0.7 (*1*)	13.9 ± 1.0 (*2,3,4,5*)	34.5 ± 1.5	1.5 ± 1.5

[a]Letters indicate stages in the sequence to left of entry, i.e. for the same species, that are significantly different at $p < 0.05$.

[b]Figures indicate significant differences in the same column, i.e. among the different species. Values are means ± S.D. ($n = 4$).

increased further again (Table II). Thus, in every species tested the system continued to function under dark conditions, and could respond to the higher dose, i.e. the system was not yet saturated. Conversely, when left without top-up doses (Figures 1 and 2), concentrations fell below detection limits, indicating that removal activity was maintained at very low VOC concentrations, regardless of lighting conditions.

After the plants were removed (stage *f*) and the potting mix returned to the chambers, still in the dark, with a new standard dose of benzene (Figures 1 and 2; Table II), some VOC removal continued in all species. However, except with *H.*

forsteriana, the removal rates were lower than in the presence of the plant, and in two species (*E. aureum* and *D. marginata*) the rates were significantly less than at the initial post-induction stage (stages *c* or *d*). The lowered rates after plant removal could have been the result of the inevitable disturbance of the root-zone during the removal process, and hence the level of microbial activity, or alternatively they point to the plant and micro-organisms each making a significant contribution to VOC removal. Studies are continuing to elucidate the relative roles of plant and substrate further.

On a per-pot (i.e., per-chamber) basis, there were some significant differences among the plant species in the post-induction, 24-h averaged VOC removal rates (Table II). *D.* 'Janet Craig' showed the highest removal rate immediately after induction (stage c), more than twice that of the slowest, *H. forsteriana.* However, some species later showed a greater proportional response than others to the application of the doubled dose of benzene (stage *e*), so that their rates then exceeded that of *D.* 'Janet Craig'.

The activity of the potting mix micro-organisms in the removal process was tested after completion of the test-chamber experiments. It was found that, although across the seven plant species both the potting mix samples and the broth/vermiculite cultures initially showed some differences in benzene removal rates, it was not for long. By the third top-up dose (i.e., end of the 3rd day), potting mix samples from all plant species removed approximately 97% of the benzene in 24 h, while the micro-organism cultures removed approximately 95%. The results confirmed the activity of the substrate micro-organisms in VOC removal, and is the first direct demonstration of their ability for VOC degradation utilizing the gas phase of the compound. The findings are a first step towards characterizing the active components of the microbial community in VOC biodegradation, and work is continuing on the effects of VOCs on the micro-ecology of the potted-plant system.

3.3. Removal rates on alternative bases

Table III presents the post-induction VOC removal rates (Stage *c*) with the seven plant species, expressed as a function of the various plant and potting mix parameters listed in Table I. A comparison of the removal rates shown in Table II (column 1) with those in Table III, demonstrates how changing the basis of the calculation gives very different impressions of effectiveness among the species. However, overall, the calculations on none of these plant parameters result in the same order of effectiveness as on the 'per plant' i.e., 'per pot' basis. This is a further pointer to the removal being the result of the integrated operation of the plant-substrate microcosm. The results on various individual plant parameters might, however, be useful in developing the system further, by indicating how much leaf or root material is needed for a certain VOC removal capacity. Meanwhile, since the standard of use of indoor potted-plants by both horticultural and building industries is per pot of

TABLE III

Rates of benzene removal (24 h averaged) after induction (i.e. stage *c*) expressed on basis of alternative plant/potting mix parameters (cf. column 1, Table II)

	24 h-averaged rate of VOC removal in stage *c* of experimental sequence (i.e. post-induction) of plant or potting mix parameters			
Plant species	ppm d^{-1} m^{-2} leaf area	ppm d^{-1} g^{-1} dwt shoots	ppm d^{-1} g^{-1} dwt roots	ppm d^{-1} kg^{-1} dwt pot-mix
Dracaena 'Janet Craig'	188 ± 48 (*3,6*)	1.6 ± 0.4	6.1 ± 1.8 (*2,3,4,6*)	60.5 ± 15.2 (*3,7*)
Epipremnum aureum	88.7 ± 3.1 (*3, 5*)*	2.1± 0.0	1.0 ± 0.1 (*1, 4*)	32.6 ± 0.8
Dracaena marginata	337 ± 25 (*2, 4, 5, 7*)	1.4 ± 0.2	1.8 ± 0.65 (*1,4*)	27 ± 1.8 (*1*)
Schefflera 'Amate'	123 ± 7.5 (*3*)	1.2 ± 0.8	11.1 ± 1.0 (*1,2,3,5,6,7*)	49 ± 3.4 (*7*)
Spathiphyllum 'Petite'	212 ± 22 (*2,3,6*)	1.6 ± 0.2	4.4 ± 1.0 (*4*)	53 ± 5.6 (*7*)
Spathiphyllum 'Sensation'	59 ± 4.3 (*3,6,7*)	1.1 ± 0.1	1.7 ± 1.0 (*1,4,7*)	36 ± 2.1
Howea forsteriana	167 ± 22 (*3*)	1.1 ± 0.1	3.8 ± 0.3 (*4*)	15.6 ± 1.0 (*1,4,5*)

*Figures in parentheses indicate significant differences in the same column among the different species ($p < 0.05$). Values are means ± S.D. ($n = 4$).

specified size, this would seem to be the most useful basis of comparison of VOC removal efficiencies (i.e. as used in the figures and in Table II).

4. Discussion

The results demonstrate the capacity of the potted-plant-substrate microcosm to remove gaseous-phase benzene from indoor air. With all species tested, the microcosm reduced or eliminated high air concentrations of the VOC; was equally effective in light or dark; and showed rates which increased more or less linearly with dose across the concentrations tested, showing that with no species was the system saturated by the contaminant. Conversely, the system could also remove very low residual VOC concentrations, since levels were effectively reduced to below detection limits before being renewed (Figures 1 and 2).

On a per-pot (i.e., per microcosm) basis, there was a range of post-induction removal rates (from approximately 12–28 ppm d^{-1}) among the seven plant species tested. Our previous studies (Wood *et al.*, 2000, 2002; Tarran *et al.*, 2002) using three of the species, also showed that different species showed different rates of

removal with different VOCs (benzene and *n*-hexane). The results suggest that a mixture of potted-plant species is (without further horticultural development) likely to be most effective in mixed VOC removal in the indoor environment.

Under the conditions of these experiments, substrate micro-organisms played a major role as agents of VOC removal. However, the results show that the plant is also involved, in some cases by measurable absorption, and in all cases via the maintenance of the root-zone microbial community, which is in line with what is known of normal plant/rhizosphere relationships. The system is stimulated by exposure to the chemical, i.e., during acclimation to exposure, and maintains its heightened performance with repeated doses, indicating the induction of one or more biochemical pathways in substrate bacteria and possibly also plant, to degrade the chemical on a sustainable basis (provided the potted-plant is nurtured in the normal way).

The biochemical issues are being further researched, as well as changes in the microbial community, which might well occur in favour of species which can utilise the VOC. On the basis of these findings, it would seem that some of the models and empirical analyses of the results of other studies on the uptake of semi-volatile organic compounds (SOCs) by plants (e.g. Peck and Hornbuckle, 2002), which have relied only on presumed cuticular and stomatal leaf absorption, should be re-examined to investigate the possible, indeed likely, role of substrate micro-organisms in the disappearance of the substance.

A preliminary follow-up study in this laboratory has shown that VOC removal rates on a per-pot basis in the range reported here (Table II), would account for from 10 to 20% of ambient VOC levels in a flow-through situation with a 0.5 air change per hour, which represents a significant reduction in the contaminant load of indoor air (Tarran *et al*., 2002), and the system is amenable to further improvement. Several European and North American enterprises are already developing the integrated use of plant materials and 'plant-filtration' boxes, as part of building design or as later installations. In a parallel development, 'biofilter reactors' based upon air flows across compost, peat beds or activated carbon systems, are being designed as part of bioengineering solutions for the removal of air-borne VOCs from industrial processes (Bibeau *et al*., 2000; Marek *et al*., 2000; Mohseni and Allen, 2000).

The indoor potted-plant/growth medium microcosm potentially offers several advantages as a biofilter system. Oxygen transfer to soil-borne microbial communities is enhanced, and gas-phase diffusion in the soil facilitated, by the presence of plants, providing appropriate conditions for compounds to be degraded aerobically (which means more rapidly and effectively). The potted-plant system is also portable and hence flexible, and of considerable species diversity, which presumably also reflects substrate microbial diversity (a matter which has never been explored for indoor plant species, though it has been extensively studied for some edible crop species). It should be possible to develop improved indoor potted-plant/growth media combinations with enhanced capacities for cleaning indoor air, as part of a

'green chemical' solution to improving the indoor environment, while continuing in their traditional role of contributing living beauty to the aesthetics of the indoor environment.

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